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Experimental research on spray evaporative cooling system applied to air-cooled chiller condenser

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ABSTRACT

This study investigates the performance of a refrigeration unit by applying a spray evaporative cooling system to an air-cooled chiller. Experiments are conducted in the temperate monsoon climate region by combining the spray evaporative cooling system with the air-cooled chiller. Moreover, this study adopts a new gas–liquid two-phase swirl nozzle, which is independently developed and characterized by high atomization quality and low energy consumption. The experimental results show that the power of the compressor is reduced, while the COP (Coefficient of Performance) of the air-cooled chiller increases by 4%–8% after the intervention of the spray evaporative cooling system. The spray cooling system contributes to an electricity savings of 2.37%–13.53% in air-cooled chiller systems. If a more reasonable spray evaporative cooling mode is used, such as controlling the water flows according to the cooling capacity and arranging the nozzle positions and angles reasonably, the COP of the air-cooled unit will be further improved.

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1. Introduction

With the increasing demand for energy, energy saving has become the focus of attention in recent years. At present, China's construction energy consumption accounts for 20% of the total energy consumption (Xu and Wang, 2020). High energy consumption in air conditioning system and it is estimated that by 2100, the power consumption of air conditioning will be 33 times higher than the current power consumption (Vende et al., 2018). It can be seen that air conditioning energy saving has great potential. In summer, the high air temperature around the condenser of the air-cooled refrigeration units leads to the increasing of the power consumption, even causes the unit shut-down due to the back pressure exceeding the limit. In order to solve the above problems, using spray evaporative cooling system to cool the air around the condenser demonstrates to be a good way. The spray evaporative cooling system relies on the latent heat absorbed by the evaporation of water to achieve the purpose of cooling, and it can be used in both water-cooled and air-cooled air-conditioned systems. Regarding to the study of water-cooled air conditioning system combined with evaporative cooling technology, Gilani et al. (2019) developed a novel configuration of shower cooling tower combining a liquid desiccant system equipped with the internal cooling system and mathematically modeled separately.

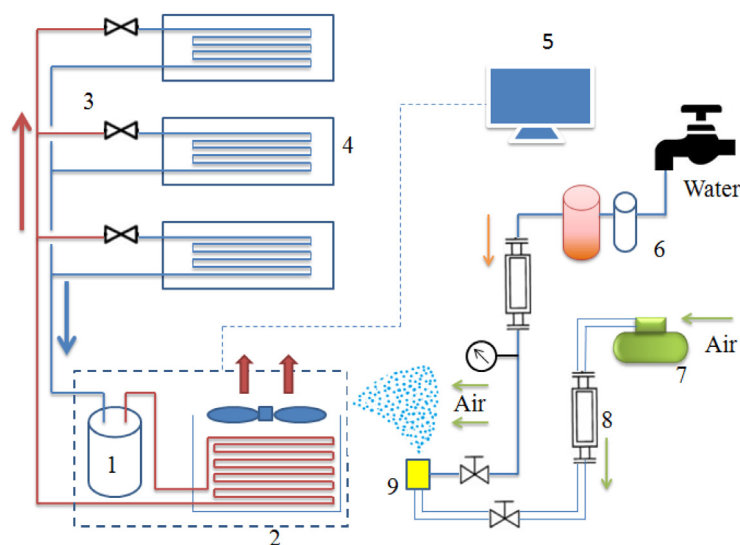
When the spray evaporative cooling system was applied to air-cooled air-conditioning systems, it could provide thermal comfort conditions when relative humidity and the outdoor air temperature were in the range of 10%–60% and 27–41 °C, respectively (Gilani and Poshtiri, 2014).

Many scholars have done simulation research on the spray evaporative cooling system combined with condenser. Wang et al. (2015) studied the influence of spray cooling with different water quantities and nozzle angles on the ambient air temperature field around the condenser. The results showed that the temperature distribution of the air around the condenser was more uniform with the increase of spray quantities and spray angles, which effectively improved the heat dissipation capacity of the condenser. Harbyn et al. (2016) summarized the operation principles of evaporative-condensers, theory of heat rejection, water evaporation rate and application in air conditioning system of evaporative condenser. Wang et al. (2008) used numerical calculation software and took the air-cooled unit of 200 MW as the research object, carried out three-dimensional numerical simulation of the situations with and without atomization cooling device respectively, and analyzed the atomization process of fog droplets and the heat-wet exchange effect of fog droplets in air-cooled units in detail. Yu and Chan (2005) simulated the operation condition of adding spray cooling equipment to air-cooled unit. The results showed that spray cooling equipment could reduce the condensation temperature by 2.1–6.2 °C and the refrigeration unit power by 1.4–14.4%, and increase the refrigeration capacity by 1.3–4.6%. Shirmohammadi and Gilani (2019) established the mathematical model to discuss influence of the impacts of channel dimensions,

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1. Compressor 2. Condenser 3. Expansion valve 4. Evaporator 5. Computer
6. Soft water equipment 7. Air compressor 8. Rotameter 9. Nozzle

Fig. 1. Schematic of the spray cooling for air-cooled chiller system.

plate spacing of heat exchanger, relative humidity, air flow velocity, wettability factor of surface of the indirect–direct evaporative cooling system on heat exchanger efficiency at 40 °C and 30% relative humidity, and selected appropriate evaporative system for variety of climates of some cities of Iran.

In experimental research of the spray evaporative cooling system, Yan et al. (2010) used a kind of closed circulating gas-assisted four-spray system with R134a as the working fluid to cool the electronic chip. The results showed that both the heat transfer capacity and the temperature uniformity of the heating surface were increased with the increasing of the flow rate. Cheng et al. (2010) studied the influence of spray height and other factors on heat transfer of spray cooling by experimental method, and summarized the heat transfer mechanism of spray cooling according to the experimental data and spray characteristics, and found that the spray height had an optimal value. Liu et al. (2016) obtained similar conclusions through experiment. About the spray cooling system combined with air-cooled units, Martínez et al. (2016) tested a split air conditioning system combining evaporative cooling pads, and determined the optimal size of the cooling pads. The cooling capacity was increased by 1.8% and the compressor power consumption was reduced by 11.4% with the 100 mm thickness pad. Hajidavalloo and Eghtedari (2010) did a similar experiment using the Mitsubishi split air-conditioner. Liu et al. (2015) proposed an air conditioning system combining dual independent evaporative condenser and discussed the effect of various factors such as evaporator water inlet temperature, air dry-bulb temperature and etc. on COP and cooling capacity through experiments. Huang and Ye (2015) built an experimental platform using a new supersonic spray cold water set, which not only produced almost no sewage and residual water but also reduced the inlet temperature of the condenser by 5.4 °C. Wang et al. (2014) found that the recovery period of the system was about 2–3 years. Kabeel et al. (2017) found that the higher the ambient air temperature, or the lower the relative humidity of the surrounding air, the greater the efficiency of the spray system.

Most of the above experiments and simulation research used the existing spray system on the market and under the ideal conditions of dry and hot. In this paper, a new spray system of gas–liquid two-phase swirl atomizer is applied to commercial

air-cooled units in the real outdoor environment of Tianjin in summer, and the effect of this spray cooling system is discussed. This kind of spray system has high atomization quality and low energy consumption, as the actual spray power consumption is only 7.59 W/kg.

2. Experimental setting up

2.1. Experimental system

There is no doubt that the nozzle is the core component of the spray cooling system. The atomization quality of the nozzle directly affects the heat and mass transfer of tiny droplets and evaporation efficiency. The nozzle used in this paper is a new self-developed gas–liquid two-phase swirling atomizing nozzle. Using the bubble cutting technology, the softening water is atomized into micron-sized droplets. The atomized droplet size of the nozzle is small and evenly distributed. The atomized droplet size can reach D32 less than 20 μm with the low ratio of mass air/ liquid of 0.06–0.2. Moreover, the nozzle has a wide range of working pressure and a small liquid flow rate, which can maintain a stable spray with a liquid flow rate of 2–8 kg/h at a working pressure of 0.2–0.6 MPa. In addition, the nozzle and the outer case are connected by thread, which is simple in structure and convenient in disassembly and cleaning. The nozzle style can be easily changed to meet the needs of different situations. Most importantly, the energy consumption of the nozzle is the key factor for the energy saving of the whole spray system. The actual spray power consumption is only about 7.59 W/kg while maintaining high atomization quality, which plays a good energy saving role in the spray cooling process.

The experimental system mainly includes four components: spray system, water softener, air-cooled unit and parameter monitoring platform. The spray system includes: atomized nozzle, air compressor, rotameter, pressure reducing valve, pressure gauge, check valve, cut-off valve, frame, pipes. The water source side of the spray system is directly connected to the tap water through the water softener device, and the steady water pressure provided by the water supply is 0.3 MPa. Fig. 1 is the schematic of the spray cooling for air-cooled chiller system, and Fig. 2 is the photographs of the spray cooling for air-cooled chiller system



Fig. 2. Photographs of the spray cooling for air-cooled chiller system and soft water system.

and soft water system. Because the mist water is softened, even if the spray system runs for a long time, it will not scale, and the condenser surface can be maintained in a clean condition. The air source side of the spray system is connected with an air compressor, which can provide a stable pressure. By adjusting the two flowmeters of liquid and gas, the spray can be kept stable. When the water flow rate of a single nozzle is 3–5 kg/h, the atomizing effect of the nozzle is good enough to meet the requirement of rapid evaporation. It can quickly perform the endothermic evaporation process and reduce the ambient temperature of the droplets, which is very critical for spray cooling. The excess water will cause the problem of wasting water, it can be seen from Fig. 3 that when the water flow is 16 kg/h, there is little water left in front of the condenser, while when the water flow is 20 kg/h, a small amount of water is left, so the water flow is not been further increased. However, the lack of water cannot guarantee the effective promotion of COP. Therefore, three different water flow rates (m_f) of 12 kg/h, 16 kg/h, and 20 kg/h are set up to further investigate the effect of the difference in water mist on the unit performance. This experiment used Fujiwara new oil-free bass air compressor, the power is 750 W, the voltage is 220 V, the air storage tank capacity is 24 L, and the rated exhaust pressure is 0.8 MPa. Air-cooled units are used by Haier multi-link air-conditioning unit, the model is RFC735MXMLYA. The rated cooling capacity is 50.4 kW and the refrigerant is R410A. During the experiment, due to the limited number of indoor units that can be turned on, there are 20 and 10 indoor units opened during the operating mode of horizontal and vertical spraying, and the refrigeration capacity are about 40 kW and 20 kW, respectively.

2.2. Arrangements of the nozzles

The experiment used four nozzles, and there are two arrangement methods: horizontal spraying and vertical spraying. Particularly, horizontal spraying is to arrange four nozzles at a distance of 1200 mm from the ground and 850 mm from the front air inlet of the unit, water mist is sprayed horizontally to the front of the unit; Vertical spraying is to arrange four nozzles in the three air inlet of the unit, two on the front of the unit and one on both sides of the unit. All four nozzles are at the bottom of the unit, and the spray direction is from the bottom to top. Because the optimum atomization area of the nozzle in this experiment

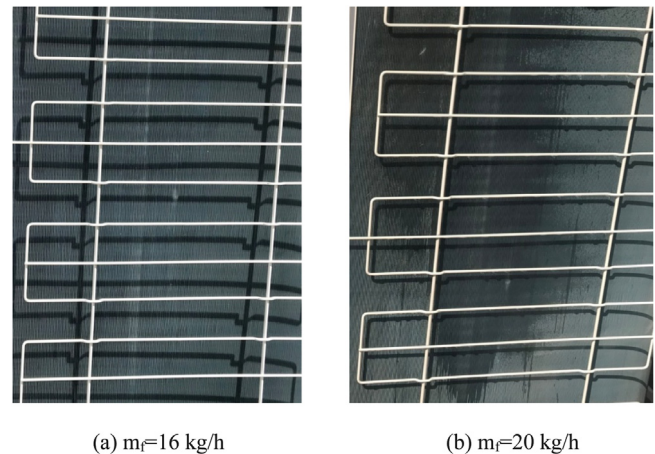


Fig. 3. Residual water on the front of the condenser.

is within the range of 500–1000 mm from the nozzle outlet, and the two fans at the top of the air conditioning unit will make the negative pressure of the upper part of the unit larger and take more air into the unit. In this way, the best atomization stage will be in the top half of the unit. After the evaporation of atomized particles takes away the heat of surrounding air, the cooling air will enter the condensing unit, which will reduce the condensing temperature and ultimately improve the operation performance of the unit (see Figs. 4 and 5).

2.3. Measuring instruments

The environmental temperature and humidity of this experiment are measured by temperature and humidity sensors. The accuracy of temperature measurement is ± 0.2 °C, the accuracy of humidity measurement is $\pm 2\%$. The cooling capacity is calculated through real-time monitoring parameters of the unit, the maximum deviation is about 15%, and the power consumption is calculated by the integration of power and time by monitoring the input voltage and current of the power supply, and the deviation is about 5%. The values of power consumption and cooling capacity can be obtained by detecting the platform.

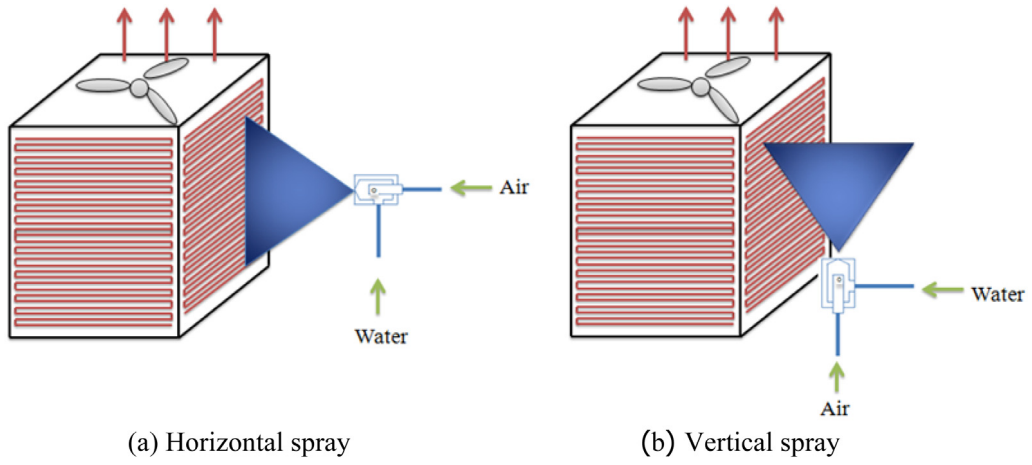


Fig. 4. The arrangement of spraying mode.

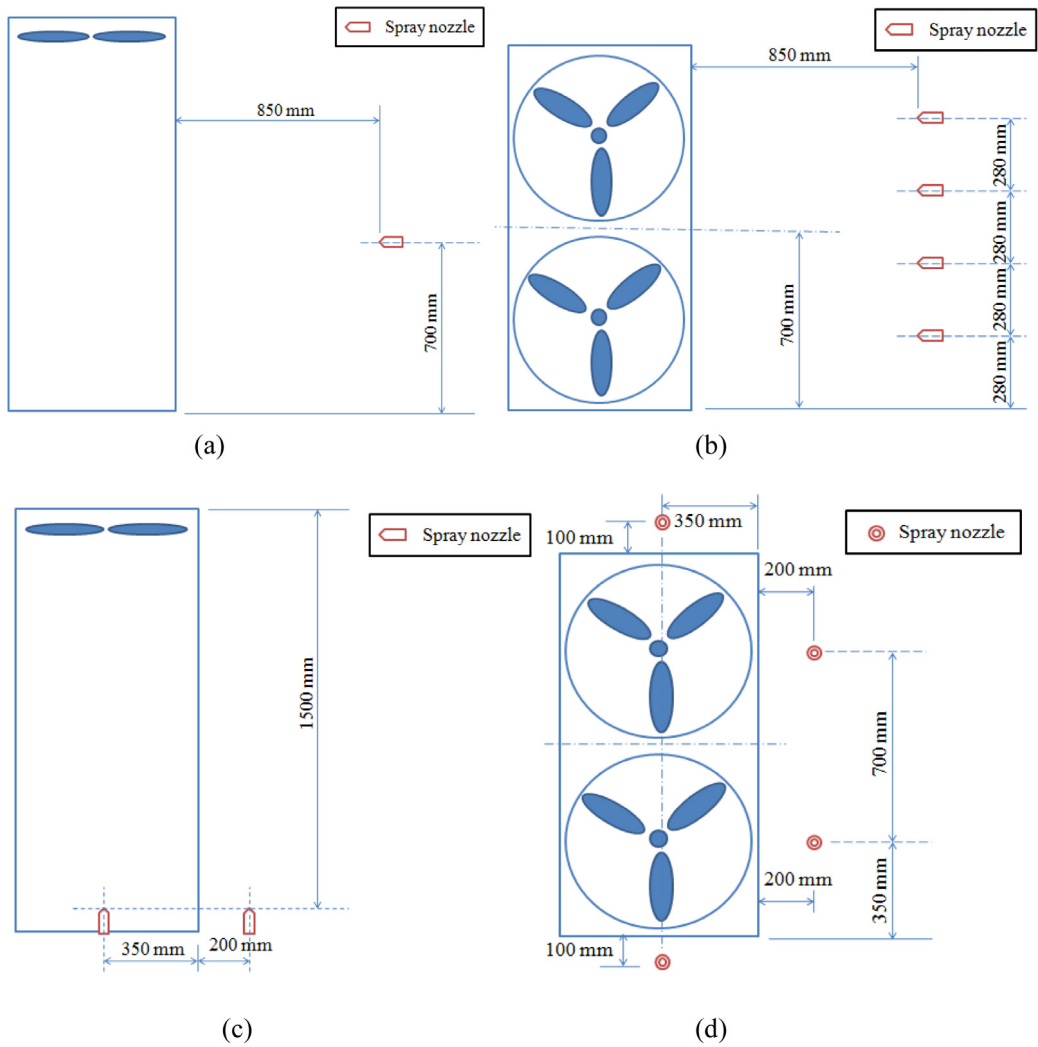


Fig. 5. Nozzle position: (a) Lateral view of horizontal spray, (b) Top view of horizontal spray, (c) Lateral view of vertical spray, (d) Top view of vertical spray.

3. Results and discussion

3.1. Effect of water flow on the performance of air conditioning system

When using the horizontal spraying, the average temperature and relative humidity of outdoor environment before spraying were 34.9 °C and 39% respectively, and when using the vertical spraying, the average temperature and relative humidity of outdoor environment before spraying were 33.0 °C and 32%, respectively. The COP means coefficient of performance, which is defined as the ratio of cooling capacity to power consumption of the air-cooled units:

$$\text{COP} = \frac{Q}{E} = \frac{Q}{E_{\text{com}} + E_{\text{fan}}} \quad (1)$$

where Q (kW) is the cooling capacity of the air-cooled units and E (kW) is the power consumption of the air-cooled unit, including the power consumed by refrigerant compressor E_{com} (kW) and the power consumed by fans E_{fan} (kW), and these parameters are measured on the platform directly. Figs. 6 and 7 show the changes of COP of air-cooled units under different water flows ($m_f = 12$ kg/h, 16 kg/h and 20 kg/h) when using horizontal or vertical spraying.

It could be seen from the figures that the spray evaporation device can effectively improve the COP of the air-conditioning unit. When using horizontal spraying and the water flow was 12 kg/h, the average COP rose from 3.70 to 3.84, increased by 3.78%; when the water flow was 16 kg/h, the average COP rose from 3.52 to 3.72, increased by 5.68%; and when the water flow was 20 kg/h, the average COP rose from 3.58 to 3.84, increased by 7.26%. When the vertical spraying was used and the water flow was 12 kg/h, the average COP rose from 3.78 to 3.94, increased by 4.23%; and when the water flow was 16 kg/h, the average COP rose from 3.78 to 3.96, increased by 4.76%; and when the water flow was 20 kg/h, the average COP rose from 3.60 to 3.90, increased by 8.33%. It can be seen that the optimum effect of spray evaporation device on air conditioning unit can be improved by properly increasing spray water flow.

3.2. Impact of different part load conditions on the performance of the air-cooled unit with a spray system

The cooling capacity of the air-cooled unit and the water flow of the spray system play an important role in evaluating the growth rate of the COP of the air cooling unit. In this study, the cooling capacity of the air-cooled unit and water flow of the spray system have different degrees of impact on unit performance.

Eq. (2) defines ΔCOP as the growth rate of COP:

$$\Delta\text{COP} = \frac{\text{COP}_{wi} - \text{COP}_{wo}}{\text{COP}_{wo}} \quad (2)$$

where COP_{wi} is the COP of the air-cooled unit with spray cooling system, and the COP_{wo} is the COP of the air-cooled unit without spray cooling system.

Fig. 8 demonstrates that the percentage of the COP increases under different water flow and different cooling capacity when using horizontal spray and vertical spray. As can be seen from Fig. 8(a), when the cooling capacity of the air-cooled unit is about 20 kW, the growth rate of the COP increases first and then decreases with the increase of the water flow. This is because when the water flow is 20 kg/h, the excess water converges on the condensing coil to form a water film, which reduces the heat transfer between the condensing coil and the surrounding air. When the cooling capacity of the air-cooled unit is about 40 kW, the growth rate of the COP increases with the increase

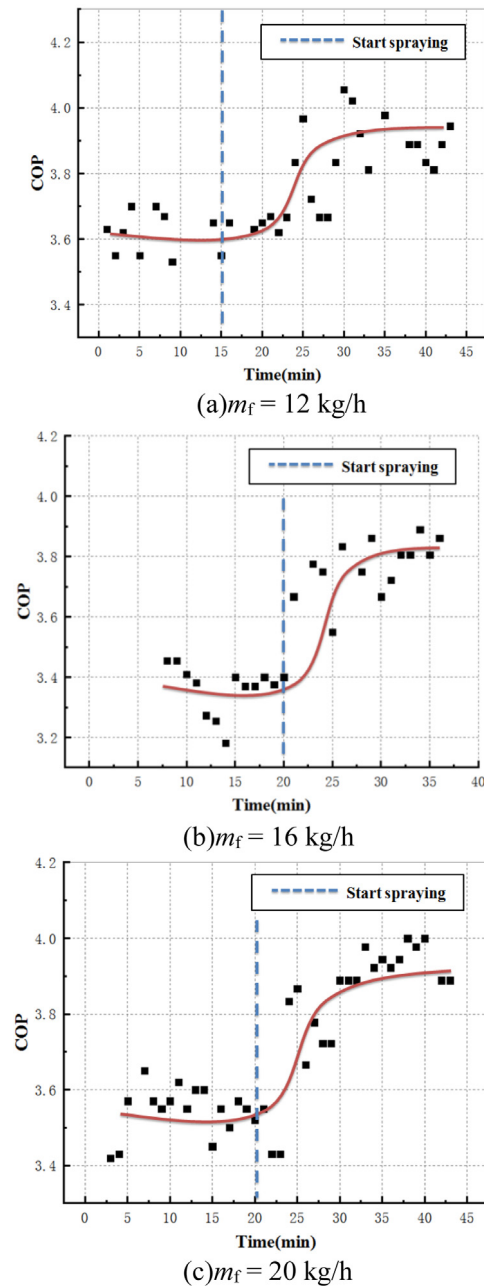


Fig. 6. The changes of COP in vertical spraying.

of water flow. The result is that when the refrigerating capacity of the unit increases, the compressor power increases and lead to the increase of condensation temperature. At this time, more water mist needs to be evaporated to reduce the condensation temperature and improve the performance of the unit. Therefore, when the cooling capacity of air conditioning system increases, it needs to provide more water. When cooling capacity of the system is small, the water quantity should be reduced reasonably and the waste of water should be avoided. The similar law can be found from Fig. 8(b).

3.3. Comparison of two different spray modes

Compared with Fig. 8(a) with (b), it can be found that the effect of vertical spraying is better than that of horizontal spraying, and the ΔCOP of vertical spraying is 0.28–1.94 higher than that

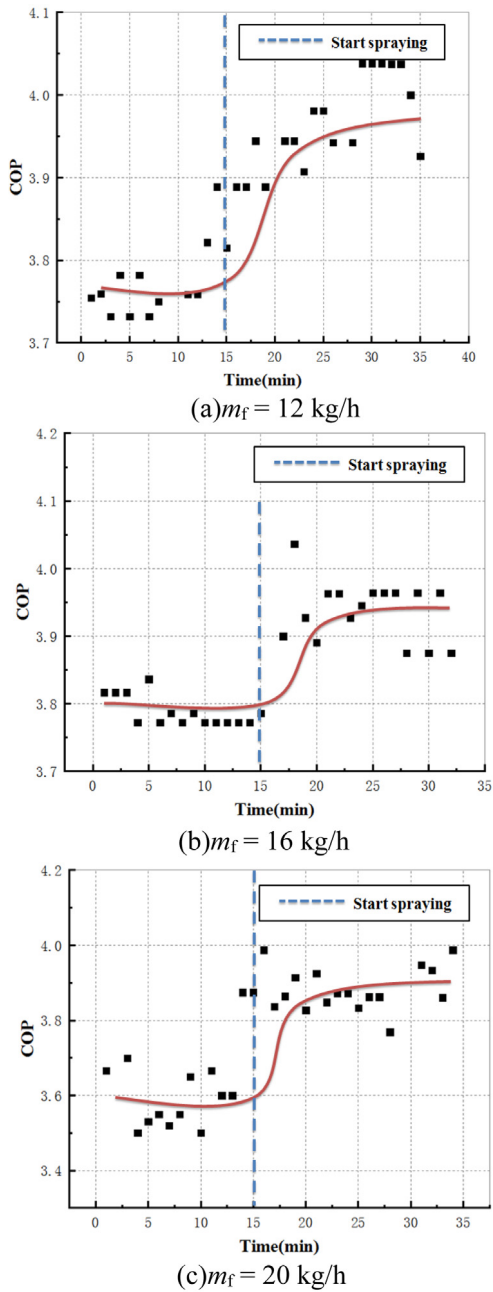


Fig. 7. The changes of COP in horizontal spraying.

of horizontal spraying. The main reasons are as follows: first, when vertical spray is used, compared with horizontal spray, the retention time of droplets in the air is shorter, and it is easier to fall to the ground before it evaporates; secondly, the contact area between the water mist and the air in front of the inlet of the outdoor unit is larger in vertical spray, and more air will be fully cooled and flow through the condenser surface; what is more, when horizontal spray is adopted, the distance between each nozzle is so close that makes some small droplets gather together and leads to the larger particle size and the slower evaporation rate. When spraying vertically, there is almost no overlap in the spray area, which is conducive to the evaporation of droplets.

Therefore, the installation position of the nozzles has an important influence on the cooling effect of the spray cooling device, when using the spray cooling system, the installation position of the nozzle should be reasonably arranged to prolong the stay time

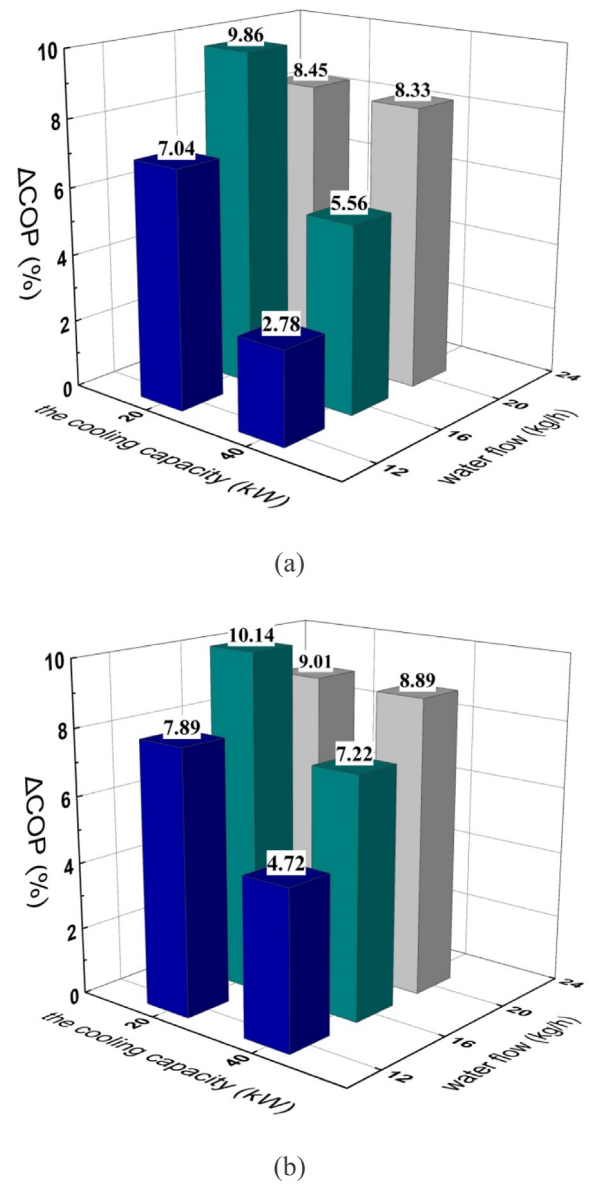


Fig. 8. Three-dimensional histogram of ΔCOP with different cooling capacities and different water flows: (a) horizontal spray, (b) vertical spray.

of the water mist in the air and to make the water mist contact with as much air as possible, at the same time, avoid overlapping the spray range of each nozzle.

3.4. Effects of ambient temperature and relative humidity

From previous studies, relative humidity and ambient temperature are also the main parameters that affect the spray cooling effect. Most of the existing studies have been separate studies of the two. In this section, different combinations of the two will be studied.

It can be clearly seen from Fig. 9 that the distribution of the histogram is not uniform, but an approximately upper triangular distribution, which is caused by the climatic conditions of Tianjin, there is almost no low temperature and low humidity in summer in Tianjin. It can be seen from Fig. 9 that the COP only increases by about 2% when the ambient temperature is 25 °C, and increases by about 6%–9% when the ambient temperature is 40 °C. Under the ambient temperature of 25 °C, the effect of relative humidity

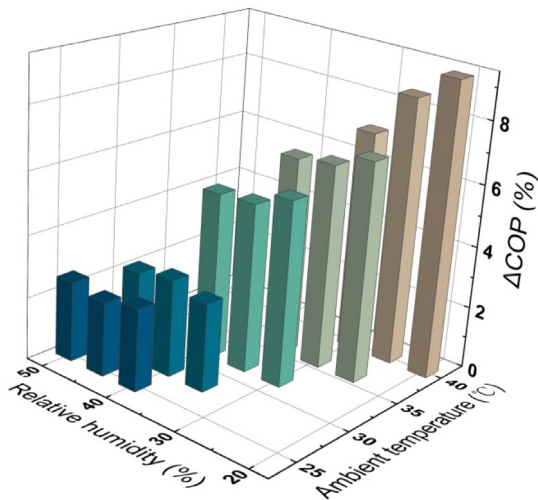


Fig. 9. Three-dimensional histogram of ΔCOP under different combinations of relative humidity and ambient temperature.

on the improvement of ΔCOP is unobvious. While under the ambient temperature of 40 °C, decreasing the relative humidity from 50% to 40% can increase the ΔCOP by 2.7. In summarize, the water is easier to be evaporated under higher ambient temperature and lower relative humidity, which is conducive to decrease the condenser temperature and improve the COP of air conditioning system.

3.5. Air conditioning unit operation optimization effect and economic analysis

This experiment used two-phase cyclone atomized nozzles and the power consumption is only 7.59 W/kg. Taking the vertical spraying of 12 kg/h as an example, the spray system consumes $12 \times 7.59/1000 = 0.09$ kW/h. Before the spraying, the average cooling capacity of the air conditioning unit is 21.02 kW, the average power consumption is 5.56 kW, and the COP is 3.78. During the process of each experiment, the indoor environment is stable and the refrigerant flow is constant, so the change of cooling capacity is only 0.01–2 kW. The average cooling volume of the air-conditioning unit is 21.03 kW, and the average power consumption of the air-cooled unit is reduced to 5.34 kW, the total power consumption with spray was 5.43 kW. Therefore, the COP' is defined as the ratio of refrigeration capacity collected on the platform to the total power consumption of the whole system:

$$\text{COP}' = \frac{Q}{E'} = \frac{Q}{E + E_c + E_p} \quad (3)$$

where E' (kW) is the total power consumption of the whole system, which is the sum of nozzle energy consumption and air-cooled unit energy consumption. E_c (kW) and E_p (kW) are the power consumption of the compressor and the water pump, respectively. In this experiment, the water pipe is directly connected to the tap without water pump. The power of the compressor is calculated by Eqs. (4) and (5). The energy consumption of the nozzle is mainly composed of a compressor and a water pump. It needs to be explained here that the power consumption of the soft water device is too small to be negligible.

$$E_s = \frac{n\zeta}{n-1} R_g T \left[\left(\frac{P_c}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \quad (4)$$

$$E_c = 3600 E_s Q_a \quad (5)$$

where n is variable index, ζ is the margin factor of the compressor, R_g (J/kg·K) is the ideal gas constant of air, T (K) is the air temperature, P_1 (MPa) is the inlet pressure of the compressor, P_c (MPa) is the outlet pressure of the compressor, Q_a (kg/h) is the air consumption of nozzle. Where the value of n and R_g are 1.25 and 287, respectively. E_s (kJ/kg), actual energy consumption per unit mass of compressed air, could be obtained by Eq. (4). Then, E_c could be obtained by Eq. (5).

The COP' of the total system was 3.87, and it was increased by 2.38% actually. Through this method, Table 1 can be obtained. As can be seen from Table 1, after using gas–liquid two-phase cyclone atomized nozzles, the total power consumption of the system is decreased by 0.13–1.26 kW, and the total system COP' was increased by 2.38–6.38%. Meanwhile, the operation of air conditioning units has been improved. Air-cooled chillers can save 2.37–13.53% of electricity after coupling the spray system.

4. Conclusions

The rational use of spray cooling system can decrease the power consumption of air-cooled units and achieve energy-saving purposes. This study uses new self-developed gas–liquid two-phase swirling atomizing nozzles, and combines spray cooling system with air-cooled unit. The effect of spray cooling system on air-cooled unit under temperate monsoon climate is studied and the following conclusions can be drawn:

- Combining the spray cooling device with the air-cooled unit can increase the average COP by 3.78–8.33% without the calculation of the energy consumption of the spray cooling system, which effectively optimize the performance of the air-cooled unit.
- When the cooling capacity is 40 kW, the COP with the water flow rate of 20 kg/h is the highest, while when the cooling capacity is 20 kW, the optimal spray rate is 16 kg/h. It is necessary to control the water flows under suitable range so that the water mist does not have surplus and the water resources will not be wasted.
- The ΔCOP of vertical spraying is 0.28–1.94 higher than that of horizontal spraying, as in the vertical spraying, the retention time of droplets in the air is longer, the contact area between the water mist and the air in front of the condenser is larger, and there is no overlap in the spray area, which are conducive to the evaporation of droplets.
- The COP increases by about 2% when the ambient temperature is 25 °C, and increases by about 6%–9% when the ambient temperature is 40 °C. Under the ambient temperature of 25 °C, the effect of relative humidity on the improvement of ΔCOP is unobvious. While under the ambient temperature of 40 °C, decreasing the relative humidity from 50% to 40% can increase the ΔCOP by 2.7. Spray cooling system is more practical in places with high ambient temperature and low relative humidity.
- The new self-developed gas–liquid two-phase swirling atomizing nozzles can ensure the good atomization quality with low energy consumption. Even if the energy consumption of the spray cooling system is considered, the total electricity consumption can be decreased by 2.37–13.53%, and the average COP' can be increased by 2.38–6.38%.

Future scope of work

In this experiment, the effects of two spray methods and three mass flow rates on the performance of air-cooled chiller are investigated. In the future, the influence of different spray angles and other installation positions and more mass flow rates

Table 1
Actual power consumption and coefficient of performance of the system.

Spray mode	Amounts of water (kg/h)	COP'			Power consumption		
		Without spray	With spray	Relative increase (%)	Without spray (kW)	With spray (kW)	Relative decrease (%)
Horizontal spraying	12	3.70	3.80	2.70	9.76	9.18	5.94
	16	3.52	3.67	4.26	10.56	9.45	10.51
	20	3.58	3.77	5.31	9.90	9.28	6.26
Vertical spraying	12	3.78	3.87	2.38	5.56	5.43	2.34
	16	3.78	3.88	2.65	5.73	5.57	2.79
	20	3.60	3.83	6.38	9.31	8.05	13.53

of the nozzles on the improvement of the unit performance will be investigated to obtain the accurate relationship between the spraying system and air-cooled chiller.

Nomenclature

COP	Coefficient of performance
Q	Refrigerating capacity of the air-cooled units (kW)
E	Power consumption of the air-cooled unit (kW)
E_{com}	Power consumed by refrigerant compressor (kW)
E_{fan}	Power consumed by fans (kW)
m_f	Water flow (kg/h)
ΔCOP	Growth rate of COP
COP_{wi}	COP of the air-cooled unit with spray cooling system
COP_{wo}	COP of the air-cooled unit without spray cooling system
COP'	Ratio of refrigeration capacity to the total power consumption
E'	Total power consumption of the whole system (kW)
E_c	Power consumption of the compressor (kW)
E_p	Power consumption of the water pump (kW)
E_s	Actual energy consumption per unit mass of compressed air (kJ/kg)
n	Variable index with a value of 1.25
ζ	Margin factor of the compressor
R_g	Ideal gas constant of air which is 287 (J/kg·K)
T	Air temperature (K)
P_1	Inlet pressure of the compressor (MPa)
P_c	Outlet pressure of the compressor (MPa)
Q_a	Air consumption of nozzle (kg/h)

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Hua Yang: Conceptualization, Formal analysis, Funding acquisition, Investigation, Supervision, Writing - review, Resources. **Lan Rong:** Investigation, Data curation, Software, Formal analysis, Writing - original draft, Writing - review. **Xuanchen Liu:** Investigation, Data curation, Visualization, Writing - original draft, Writing - review. **Liansheng Liu:** Conceptualization, Project administration, Supervision, Validation. **Man Fan:** Methodology, Formal analysis, Writing - review & editing. **Na Pei:** Investigation, Validation.

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